VOLUME VIII: CHAPTER 9

METHODS FOR ESTIMATING GREENHOUSE GAS EMISSIONS FROM AGRICULTURAL SOILS

October 1999

Prepared by:
ICF Consulting

Prepared for:
Greenhouse Gas Committee
Emission Inventory Improvement Program

DISCLAIMER

This document was prepared for the Emission Inventory Improvement Program and the U.S. Environmental Protection Agency by ICF Incorporated, Washington, D.C. This report is intended to be a working draft document and has not been reviewed or approved for publication. The opinions, findings, and conclusions are those of the authors and not necessarily those of the Emission Inventory Improvement Program or the U.S. Environmental Protection Agency. Mention of company or product names is not to be considered an endorsement by the Emission Inventory Improvement Program or the U.S. Environmental Protection Agency.

ACKNOWLEDGMENTS

The text for this document was originally written by staff of the ICF Consulting Group in Washington, DC, drawing on a variety of sources. It has since been updated by Anne Choate, Rachel Golub, Barbara Braatz, Randy Freed, William Driscoll, and other staff of the ICF Consulting Group, Washington, D.C., for the Greenhouse Gas Committee of the Emission Inventory Improvement Program and for Ethan McMahon and Wiley Barbour of the Office of Policy of the U.S. Environmental Protection Agency. Members of the Greenhouse Gas Committee contributing to the preparation of this document were:

Peter Ciborowski, an Environmental Protection Specialist, Minnesota Pollution Control Agency
Sam Sadler, Energy Analyst, Oregon Department of Energy

CONTENTS

TABLES, FIGURES

Page

1

INTRODUCTION

The purposes of the preferred methods guidelines are to describe emissions estimation techniques for greenhouse gas sources in a clear and unambiguous manner and to provide concise example calculations to aid in the preparation of emission inventories. This chapter describes the procedures and recommended approaches for estimating greenhouse gas emissions from agricultural soil management.

Management of agricultural soils can lead to both nitrous oxide (N_2O) and carbon dioxide emissions. A number of agricultural activities add nitrogen to soils, thereby increasing the amount of nitrogen available for nitrification and denitrification, and ultimately the amount of N_2O emitted. These activities may add nitrogen to soils either directly or indirectly. Direct additions occur through various cropping practices (i.e., application of synthetic and organic fertilizers, daily spread of animal wastes, production of nitrogen-fixing crops, and incorporation of crop residues), and through animal grazing (i.e., direct deposition of animal wastes on pastures, range, and paddocks by grazing animals[1]). Indirect additions occur through two mechanisms: (1) volatilization of applied nitrogen (i.e., fertilizer and animal waste) and subsequent indirect emissions of that nitrogen as ammonia (NH_3) and oxides of nitrogen (NO_x); and (2) surface runoff and leaching of applied nitrogen.[2]

In addition to N_2O, carbon dioxide flux occurs in agricultural soils. Carbon dioxide flux from changes in non-forest carbon stocks are associated with four categories of land-use/land management activities: 1) liming of soils; 2) activities on organic soils, especially cultivation and conversion to pasture and forest; 3) activities on mineral soils, especially land-use change activities; and 4) changes in agricultural management practices (e.g., tillage, erosion control). The methodology for estimating CO_2 emissions from the application of lime (in the form of crushed limestone or dolomite) is presented in Section 4.5. This chapter does not include methods for the other three activities, however, because the IPCC and U.S. inventory methods can not be readily modified to apply to the state level (organic soils) or because the IPCC has not established methods for estimating emissions (mineral soils and changes in agricultural management practices).

Section 2 of this chapter contains a general description of the agricultural soil management source category. Section 3 provides a listing of the steps involved in using the preferred method for estimating each type of greenhouse gas emissions. Section 4 presents each preferred estimation method; Section 5 is a placeholder section for alternative estimation techniques that may be added in the future. Quality assurance and quality control procedures are described in Section 6. References used in developing this chapter are identified in Section 7.

---

[1] Nitrous oxide emissions from animal wastes that are managed in animal waste management systems are covered in Chapter 7, Section 4.2.

[2] Although the methodology for estimating indirect nitrous oxide emissions from sewage sludge is included in the "Agricultural Soils" section (4.5) of the *Revised 1996 IPCC Guidelines* (IPCC 1997), essentially the same methodology, as it applies to state GHG inventories, is presented in Chapter 12 (*Preferred and Alternative Methods for Estimating Greenhouse Gas Emissions from Municipal Wastewater*) of this Volume.

2

SOURCE CATEGORY DESCRIPTION

2.1 EMISSION SOURCES

Various agricultural soil management practices contribute to greenhouse gas emissions. The use of synthetic and organic fertilizers adds nitrogen to soils, resulting in emissions of N_2O. Other agricultural soil management practices, such as irrigation, tillage practices, or the fallowing of land, can also affect fluxes of greenhouse gases to and from the soil. This chapter presents methods to estimate N_2O emissions from agricultural soils and carbon dioxide emissions from liming of soils. Many other activities in the agricultural and forestry sectors are associated with GHG emissions as well. Table 9.2-1 summarizes the activities with potentially significant emissions of CO_2, CH_4, and N_2O, and provides a roadmap indicating the chapter in which each activity is addressed.

N_2O is produced naturally in soils through the microbial processes of denitrification and nitrification.[3] A number of anthropogenic activities add nitrogen to soils, thereby increasing the amount of nitrogen available for nitrification and denitrification, and ultimately the amount of N_2O emitted. These activities include application of fertilizers, animal production, indirect emissions, cultivation of nitrogen-fixing crops, and incorporation of crop residues. Another agricultural activity that leads to N_2O emissions, through the mineralization of old nitrogen-rich organic matter, is the cultivation of histosols (highly organic soils). The sources of N_2O described here are divided into three categories: (1) direct emissions from agricultural soils due to cropping practices; (2) direct emissions from agricultural soils due to animal production; and (3) emissions from soils indirectly induced by agricultural applications of nitrogen. The methodologies presented for all three components follow the methodologies in the *Revised 1996 IPCC Guidelines* (IPCC 1997). A summary of the sources included in each of the IPCC categories is provided below:

- <u>Direct emissions from agricultural soils due to cropping practices</u>. N_2O is emitted from agricultural soils due to synthetic fertilizer use, organic fertilizer use (e.g., organic fertilizer), application of animal waste through daily spread operations, crop residues remaining on agricultural fields, and biological nitrogen fixation by certain crops;

- <u>Direct emissions from agricultural soils due to animal production</u>. Estimates of N_2O from this source category are based on animal wastes that are not used as commercial fertilizer, or applied in daily spread applications, or managed in manure management systems, but instead are deposited directly on soils by animals in pastures, range, and paddocks.

[3] Denitrification is the process by which nitrates or nitrites are reduced by bacteria and which results in the release of nitrogen into the air. Nitrification is the process by which bacteria and other microorganisms oxidize ammonium salts to nitrites, and further oxidize nitrites to nitrates.

Table 9.2-1. GHG Emissions from the Agricultural and Forest Sectors
A check indicates emissions may be significant.

Activity	Associated GHG Emissions and Chapter where these Emissions are Addressed					
	CO_2	Chapter	CH_4	Chapter	N_2O	Chapter
Energy (Farm Equipment)	✔	1	✔	13	✔	13
Animal Production: Enteric Fermentation			✔	6		
Animal Production: Manure Management						
Solid Storage			✔	7	✔	7
Drylot			✔	7	✔	7
Deep Pit Stacks			✔	7	✔	7
Litter			✔	7	✔	7
Liquids/Slurry			✔	7	✔	7
Anaerobic Lagoon			✔	7	✔	7
Pit Storage			✔	7	✔	7
Periodic land application of solids from above management practices					✔	Not included [a]
Pasture/Range (deposited on soil)			✔	7	✔	9
Paddock (deposited on soil)			✔	7	✔	9
Daily Spread (applied to soil)			✔	7	✔	9
Animal Production: Nitrogen Excretion (indirect emissions)					✔	9
Cropping Practices						
Rice Cultivation			✔	8		
Commercial Synthetic Fertilizer Application					✔	9
Commercial Organic Fertilizer Application					✔	9
Incorporation of Crop Residues into the Soil					✔	9
Production of Nitrogen-fixing Crops					✔	9
Liming of Soils	✔	9				
Cultivation of High Organic Content Soils (histosols)	✔	Not included[a]			✔	9
Cultivation of Mineral Soils	✔	Not included [a]				
Changes in Agricultural Management Practices (e.g., tillage, erosion control)	✔	Not included [a]				
Forest and Land Use Change						
Forest and Grassland Conversion	✔	10				
Abandonment of Managed Lands	✔	10				
Changes in Forests and Woody Biomass Stocks	✔	10				
Agricultural Residue Burning			✔	11	✔	11

[a] Emissions may be significant, but methods for estimating GHG emissions from these sources are not included in the EIIP chapters.

Emissions from soils indirectly induced by agricultural applications of nitrogen. N_2O is emitted indirectly from nitrogen applied as fertilizer and excreted by livestock. Indirect N_2O emissions follow one of two pathways: (1) volatilization of nitrogen as NH_3 and NO_x, leading to atmospheric deposition and subsequent emissions of N_2O from the soil; and (2) fertilizer and animal waste nitrogen leaching and runoff, which enters groundwater and surface water systems, from which a portion is emitted as N_2O.

Methodologies for estimating N_2O emissions from all three source categories are included in this chapter. The chapter also provides a method for estimating carbon dioxide emissions from agricultural application of lime.

2.2 FACTORS INFLUENCING GREENHOUSE GAS EMISSIONS FROM AGRICULTURAL SOILS

A number of conditions can affect nitrification rates in soils, including water content, which regulates oxygen supply; temperature, which controls rates of microbial activity; nitrate or ammonium concentrations, which regulate reaction rates; available organic carbon, which is required for microbial activity; and soil pH, which is a controller of both nitrification and denitrification rates and the ratio of N_2O/N_2 from denitrification. These conditions vary greatly by soil type, climate, cropping system, and soil management regime. Moreover, the amount of added nitrogen from each source (e.g., fertilizers, livestock wastes, incorporation of crop residues, nitrogen fixing crops, atmospheric deposition, or leaching and runoff) that is not absorbed by crops or wild vegetation, but remains in the soil and is available for production of N_2O, is uncertain. Therefore, it is not yet possible to develop statistically valid estimates of emission factors for all possible combinations of soil, climate, and management conditions. The emission factors presented throughout this chapter are midpoint estimates based on measurements described in the scientific literature, and as such, are representative of current scientific understanding.

Nitrogen flux from animal production is dependent on the waste management system employed (if any) and the amount of waste excreted. The methodology presented here does not account for site specific conditions that could affect the amount of nitrogen excreted, or the emission factor for N_2O emissions resulting from nitrogen excretion. These conditions could include temperature, humidity, and others.

N_2O is indirectly emitted through volatilization to NH_3 and NO_x, and through leaching and runoff. Nitrogen that leaches or runs off enters groundwater, riparian areas, wetlands, rivers, and eventually the coastal ocean.

Limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$ are often applied to reduce acidity of soils. When these compounds are added to the soil they dissolve, releasing CO_2. The method used here employs two major simplifying assumptions, one dealing with timing, the other with fate of inorganic carbon. Although liming leads to emissions over a period of several years, the accounting method attributes emissions to the year in which the lime is applied. Perhaps more importantly, some fraction of the carbon loading from liming leaches to ground water, but this fate is not addressed in the methodology; all of the carbonate is assumed to be converted to gaseous CO_2.

3

OVERVIEW OF AVAILABLE METHODS

3.1 OVERVIEW OF PREFERRED METHOD

The preferred method provided in Section 4 is based on methods taken from the *IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 1997) and the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1996* (U.S. EPA 1998). Alternative methods of quantifying N_2O and CO_2 emissions from agricultural activities are under development. The IPCC is developing supplemental guidance (Good Practice Guidance) for countries to use as they develop national greenhouse gas emission inventories. The Guidance is expected to be published in spring 2000, and could be used by states to improve the inventory methodologies in this chapter. Additionally, researchers are working on a modeling approach that considers nitrogen and carbon stocks and flows and how they relate to soil systems. This approach could provide a more holistic approach to accounting for N_2O and CO_2 emissions from agricultural activities on soils. Figure 9.3-1 traces the flow of nitrogen from livestock and indicates the section where N_2O emissions from each step are addressed (note that several emission sources are addressed in other chapters).

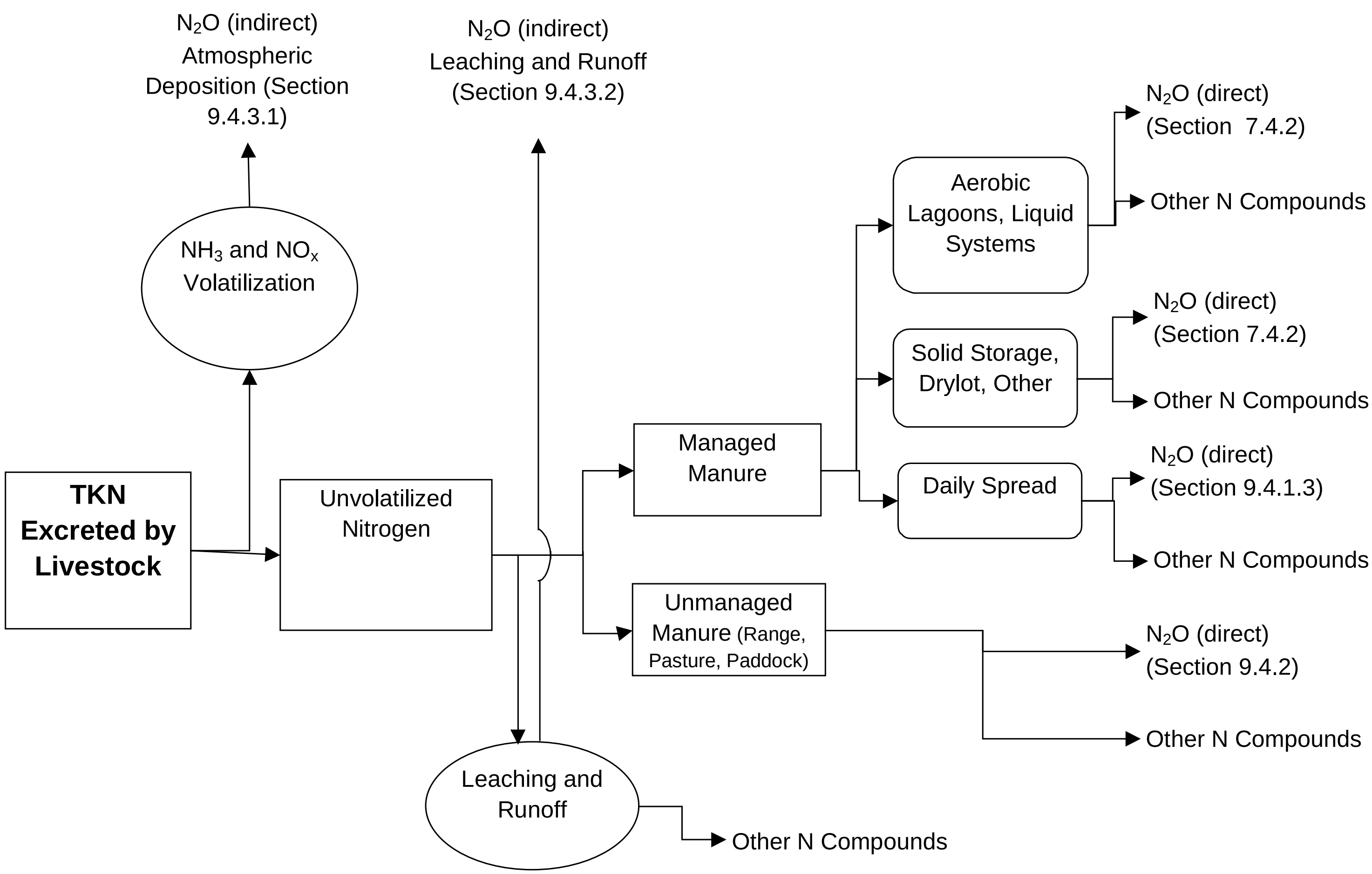
The method currently available includes five steps:

- Estimate direct emissions of N_2O from agricultural soils due to cropping practices;

> Methods for developing greenhouse gas inventories are continuously evolving and improving. The methods presented in this volume represent the work of the EIIP Greenhouse Gas Committee in 1998 and early 1999. This volume takes into account the guidance and information available at the time on inventory methods, specifically, U.S. EPA's *State Workbook: Methodologies for Estimating Greenhouse Gas Emissions* (U.S.EPA 1998a), volumes 1-3 of the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 1997), and the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 1996* (U.S. EPA 1998b).
>
> There have been several recent developments in inventory methodologies, including:
>
> - Publication of EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 1997* (U.S. EPA 1999) and completion of the draft inventory for 1990 – 1998. These documents will include methodological improvements for several sources and present the U.S. methodologies in a more transparent manner than in previous inventories;
> - Initiation of several new programs with industry, which provide new data and information that can be applied to current methods or applied to more accurate and reliable methods (so called "higher tier methods" by IPCC); and
> - The IPCC Greenhouse Gas Inventory Program's upcoming report on Good Practice in Inventory Management, which develops good practice guidance for the implementation of the 1996 IPCC Guidelines. The report will be published by the IPCC in May 2000.
>
> Note that the EIIP Greenhouse Gas Committee has not incorporated these developments into this version of the volume. Given the rapid pace of change in the area of greenhouse gas inventory methodologies, users of this document are encouraged to seek the most up-to-date information from EPA and the IPCC when developing inventories. EPA intends to provide periodic updates to the EIIP chapters to reflect important methodological developments. To determine whether an updated version of this chapter is available, please check the EIIP site at http://www.epa.gov/ttn/chief/eiip/techrep.htm#green.

- Estimate direct emissions of N_2O from animal production;
- Estimate indirect emissions from nitrogen in manure and nitrogen used as fertilizer;
- Sum emissions of N_2O from all of these sources and convert to units of metric tons of carbon equivalent (MTCE); and
- Estimate state emissions of CO_2 from agricultural application of lime.

Figure 9.3-1. Nitrogen Flows Related to Livestock



4

PREFERRED METHOD FOR ESTIMATING EMISSIONS

This section presents the preferred method for estimating emissions from agricultural soils. The sources of N_2O described here are divided into three categories: (1) direct emissions from agricultural cropping practices; (2) direct N_2O emissions from animal production; and (3) indirect emissions from nitrogen applied to agricultural soils. The methodologies presented for all three components follow the methodologies in the *Revised 1996 IPCC Guidelines* (IPCC 1997). Once emissions from each source are calculated, they are summed to yield total N_2O emissions from agricultural soils and are then converted to units of metric tons of carbon equivalent (MTCE).

Carbon dioxide emissions from agricultural application of limestone are also addressed in this chapter.

4.1. DIRECT EMISSIONS FROM AGRICULTURAL CROPPING PRACTICES

This section provides methods for estimating direct N_2O emissions from agricultural soils from the following sources:[4]

- commercial synthetic fertilizer application;
- organic fertilizer application;[5]
- animal waste applied through daily spread operations;
- incorporation of crop residues into the soil;
- production of nitrogen-fixing crops; and
- cultivation of high organic content soils.

As in the IPCC guidelines, emissions from the first five sources in this section should be estimated using a common emission factor to determine the portion of nitrogen applied to the soil that is subsequently emitted as N_2O. The emission factor used to estimate emissions from cultivation of high organic content soils is different from the direct emission factor used for other sources of direct N_2O emissions from agricultural cropping practices.

[4] The first two source categories listed in this section apply specifically to commercially available fertilizer. Because of the difficulty of obtaining data on non-commercial fertilizer use, the nitrogen applied from non-commercial fertilizer use is accounted for in the third category, animal waste applied through daily spread operations.
[5] For those familiar with the IPCC methodology for these sources, the method presented here differs because of the level of data available in the US. Data are available for states to calculate the amount of animal manure used as fertilizer, as well as the amount of other organic fertilizer applied. Therefore, the animal manure and other organic fertilizer sections are treated together.

4.1.1 SYNTHETIC FERTILIZER APPLICATION

N_2O is emitted from synthetic fertilizer application. To estimate state emissions of N_2O from the application of commercially sold synthetic fertilizer, two steps should be performed: (1) obtain data on synthetic fertilizer application in the state and (2) calculate unvolatilized applied nitrogen from synthetic fertilizer use.

Step (1) Obtain Required Data

- *Required Data*. In order to estimate N_2O emissions from synthetic fertilizer, data on the total use of synthetic fertilizer in the state are needed.

- *Data Sources*. The Fertilizer Control Official within each state should be consulted first. In the cases of Hawaii and Alaska, which do not have such an official, contact the U.S. Department of Agriculture. Additionally, state fertilizer consumption in tons of nitrogen can be found in *Commercial Fertilizers*, which is available from the Fertilizer Institute in Washington, D.C. This publication may be obtained directly from the Fertilizer Institute by calling (202) 675-8250.

- *Units for Reporting Data*. Synthetic fertilizer use data should be reported in kg N/yr.

Step (2) Calculate Unvolatilized Applied N From Synthetic Fertilizer

The IPCC specifies two different emission factors for direct and indirect N_2O emissions, therefore, direct emissions from synthetic fertilizer application must exclude the fraction of synthetic fertilizer nitrogen that is indirectly emitted through volatilization as NH_3 and NO_x. Indirect emissions from this source are covered in Section 4.3.

The fraction of synthetic fertilizer expected to volatilize is provided below.

- Fraction of total synthetic fertilizer nitrogen that is emitted as NO_x and NH_3 = 0.10 Kg (NH_3-N + NO_x-N)/kg N (IPCC 1997).

This factor is used in the equation below to calculate unvolatilized applied nitrogen from synthetic fertilizer.

Unvolatilized Applied N from Synthetic Fertilizer (kg N/yr)	=	Total Use of Synthetic Fertilizer in State (kg N/yr)	x	(1 - Fraction of Total Synthetic Fertilizer N Emitted as NO_x and NH_3) (kg N/kg N)

4.1.2 ORGANIC FERTILIZER APPLICATION[6]

N_2O is emitted from organic fertilizers applied to the soil. To estimate emissions from this source, two steps must be performed: (1) obtain data on application in the state and (2) calculate unvolatilized applied N from organic fertilizers.

[6] Typical organic fertilizers include manure, dried blood, compost, sewage sludge, and tankage.

Step (1) Obtain Required Data

- *Required Data*. The information needed to estimate nitrogen from organics is the amount of these substances used as fertilizer, the nitrogen content of these substances, and the percent that volatilizes.
- *Data Sources*. Departments within each state responsible for agricultural research should be consulted first. The amount of organics used as fertilizer may be obtained from *Commercial Fertilizers*, a report published by the Fertilizer Institute. As mentioned above, this report may be obtained directly from the Fertilizer Institute by calling (202) 675-8250.

  If state officials are not able to provide data on the amount of manure and other organics used as fertilizer, states should use the data provided in *Commercial Fertilizers. Commercial Fertilizers* provides the amount of organics (both manure and other organics used as fertilizer) used on a state by state basis. Information on other organics (dried blood, compost, dried manure, activated sewage sludge, other sewage sludge, tankage, etc.) is provided on a regional basis. Thus, a state can calculate the percentage on a regional basis of the use of manure as a fertilizer (dried manure) and the use of other organics as fertilizer. These percentages may then be applied to the state total for organics to estimate the amount of organics used in a state. An example of this calculation as well as the calculation for estimating total nitrogen from organics used as fertilizer follows.

- *Units for Reporting Data*. Data on the amount of organics used as fertilizer should be reported in kg.

Example To calculate nitrogen from the use of organics in New Jersey in 1996 the following steps should be followed:

New Jersey is located in the Middle Atlantic region. Organic fertilizer use in the Middle Atlantic region is broken out into the following categories:

20 tons of Dried Blood	4,038 tons of Other Sewage Sludge
15,195 tons of Compost	0 tons Tankage
13,060 tons of Dried Manure	7,964 tons of Other
6,618 tons of Activated Sewage Sludge	**TOTAL** = 46,895 tons

The total dried manure used in the Middle Atlantic region is 13,060 tons. The amount of other organics used as fertilizer is equal to the total amount of organics, 46,895 tons, minus the total manure, 13,060 tons; i.e., 33,925 tons of other organics are used as fertilizer. Thus the percentages of organic fertilizer in the Middle Atlantic region may be calculated by dividing the amount of manure used as fertilizer by the total amount of organics used as fertilizer in this region: (13,060/46,895) =28% of organic fertilizer is manure. Thus 72% (100%-28%) is other organics.

These percentages may then be applied to the total amount of organic fertilizer used in New Jersey, which, according to *Commercial Fertilizers 1996*, is 16,170 tons of material.

28% manure x 16,170 tons organic fertilizer in New Jersey = 4,500 tons of manure used as fertilizer

72% organics x 16,170 tons organic fertilizer in New Jersey = 11,700 tons of other organics used as fertilizer

Step (2) Calculate the Amount of Nitrogen from Organics Used as Fertilizer

It is assumed that manure used as fertilizer contains 1 percent nitrogen and that other organics used as fertilizer contain 4.1 percent nitrogen (Terry, 1997)[7]. The IPCC provides two distinct emission factors for direct and indirect N_2O emissions from fertilizer and animal waste, therefore, the total amount of nitrogen from organic fertilizer application must be reported, excluding indirect N_2O emissions resulting from volatilization of NH_3 and NO_x. Of the nitrogen in manure used as fertilizer, 20 percent volatilizes as NH_3 and NO_x; this 20 percent figure should also be applied to the other organic fertilizers (Mosier 1997). Nitrogen input from application of organic fertilizers can be calculated using these factors:

- Fraction of nitrogen in manure used as fertilizer = 0.01 (Terry 1997);
- Fraction of nitrogen in other organics used as fertilizer = 0.041 (Terry 1997); and
- Fraction of nitrogen in manure and other organics that is emitted as NO_x and NH_3 = 0.20 (Mosier 1997).

The equation used to determine unvolatilized applied nitrogen from this source is provided below.

Unvolatilized Applied N from Animal Manure and Other Organic Fertilizers (kg N/yr)	=	**[**(Amount of Manure Used as Fertilizer x Nitrogen Content) (kg N/yr)	+	(Amount of Organics Used as Fertilizer x Nitrogen Content) (kg N/yr)**]**	x	(1 - (Fraction of N in Manure and Other Organics Emitted as NO_x and NH_3)) kg(NO_x-N + NH_3-N)/kg N

Example Using the example activity data derived in "Step (1)" above, the unvolatilized applied N from this source can be calculated. Convert the data presented in the example to kg and insert them into the equation presented above, which assumes 20 percent volatilization of NH_3 and NO_x, 1 percent nitrogen content of manure, and 4.1 percent nitrogen content of organics.

4,500 tons of manure x 907.2 kg/ton = 4,085,000 kg of manure
11,700 tons of organics x 907.2 kg/ton = 10,585,000 kg of organics

Unvolatilized Applied N from Manure and Other Organic Fertilizers = [(4,085,000 kg of manure x .01) + (10,585,000 kg of organics x .041)] x (1 - .20)

= **380,000 kg N**

[7] Dr. David Terry compiles the statistics for the American Association of Plant Food Control Officials and the Fertilizer Institute's *Commercial Fertilizers* publication. He stated that manure used as fertilizer can contain from 0.5% to 1% nitrogen, and suggested we use the highest figure for our estimates. The average N content was recalculated for other organic fertilizers based on available information in *Commercial Fertilizers 1996*, Table 27.

4.1.3 APPLICATION OF ANIMAL WASTE THROUGH DAILY SPREAD OPERATIONS

Emissions from animal waste applied through daily spread operations are considered in this section because this waste is intentionally applied to the soil, as opposed to manure deposited on pasture, range, and paddock (addressed in Section 4.2). There are two steps that must be performed in order to estimate emissions from this source.

Step (1) Obtain Required Data

- *Required Data*. The information needed to estimate direct N_2O emissions from application of animal waste through daily spread operations are: population of each type of animal, typical animal mass (TAM) for each type of animal, Kjeldahl nitrogen[8] emitted per unit of animal mass for each type of animal, and the percentage of manure applied through "daily spread" (i.e., spread daily on cropland and pasture) for each type of animal.

- *Data Sources*. Departments within each state responsible for conducting agricultural research and monitoring agricultural waste practices should be consulted for animal population data. Alternatively, animal population data are provided by the National Agriculture Statistics Service of the U.S. Department of Agriculture (USDA) and can be found at the following Internet address: http://usda.mannlib.cornell.edu/cgi-usda/agency.cgi?nass. Animal population data may also be found in the *Census of Agriculture, Volume 1: Geographic Area Series*, published by the Bureau of the Census. Table 9.4-1 provides default average TAM and total Kjeldahl nitrogen excreted per unit mass for each of the major types of farm animals. The percent of manure for each animal type managed as daily spread can be found in Chapter 7, Tables 7.4-2 to 7.4-10. Where state data are available, they may be used in place of these default values.

- *Units for Reporting Data*. Animal populations should be reported in number of head.

Step (2) Calculate Nitrogen from Animal Waste Applied as Daily Spread

For each animal type *i*, multiply population times (1) the percent of manure managed as daily spread (from Tables 7.4-2 through 7.4-10); (2) the typical animal mass for animal type *i* (found in Table 9.4-1); and (3) the daily rate of nitrogen excreted by animal type *i* (also found in Table 9.4-1). Plug these constants into the equation below to determine nitrogen excretion for each type of animal.

$$\text{Total Kjeldahl N Excreted by Animal Type}_i\ (\text{kg/yr}) = \text{Population of Animal Type}_i\ (\text{head}) \times \text{Percent of Manure Managed as Daily Spread for Animal Type}_i \times \text{Average TAM}_i\ (\text{kg}) / 1000 \times \text{Kjeldahl N (kg/day) per 1000 kg mass for Animal Type}_i \times 365\ \text{days/year}$$

[8] Total Kjeldahl nitrogen is a measure of organically bound nitrogen and ammonia nitrogen.

Table 9.4-1. Constants Used to Estimate Nitrogen Excretion During Animal Production.

Animal Type	Average TAM (kg)	Total Kjeldahl Nitrogen (kg/day) per 1000 kg mass
Dairy Cow	640	0.45
Dairy Heifer	476	0.45
Feedlot Steers	383	0.34
Feedlot Heifers	391	0.34
Feedlot Cow/Other	500	0.34
NOF Bulls	680	0.34
NOF Calves	181	0.34
NOF Heifers	391	0.34
NOF Steers	383	0.34
NOF Cows	680	0.34
Swine: Market	46	0.52
Swine: Breeding	181	0.52
Sheep	70	0.42
Goats	64	0.42
Horses	450	0.3
Poultry: Layers	1.6	0.84
Poultry: Broilers	0.7	1.1
Poultry: Turkeys	3.4	0.62
Source: ASAE 1995		

Then sum the results across animal types to yield total nitrogen input from animal waste applied as daily spread. Next, adjust the total Kjeldahl nitrogen excreted per year to account for the portion that volatilizes to NH_3 and NO_x i.e., 20 percent (IPCC 1997). To do so, multiply the product of the equation above times (1-0.20), or 0.80, as shown in the equation below.

Unvolatilized Applied N from Daily Spread Operations (kg N)	=	Total Kjeldahl N Excreted in Manure that is Spread Daily (kg N)	x	0.80

Example Suppose the number of dairy cows in Ohio in a given year was 295,677 head. According to Tables 7.4-5 and 9.4-1, 45 percent of manure from dairy cows is managed in daily spread operations, the typical animal mass for dairy cows is 680 kg, and the Kjeldahl N per 1000 kg mass for dairy cows is estimated to be 0.45 kg/day. Therefore, the amount of nitrogen produced by dairy cows in Ohio during the year would be calculated as follows:

295, 677 head x 45 percent x ((680 kg/head)/1000) x 0.45 kg Kjeldahl N per 1000 kg mass x 365 days/yr = 15 million kilograms per year of Kjeldahl nitrogen from manure managed as daily spread

Adjust for nitrogen that volatilizes to NH_3 and NO_x by multiplying by 1-0.20 to determine unvolatilized applied N from manure from dairy cows that is applied in daily spread operations.

15 million kg/yr of Kjeldahl N x (1-0.20) = **12 million kg/yr unvolatilized applied N**

4.1.4 INCORPORATION OF CROP RESIDUE INTO THE SOIL

N_2O is also emitted from crop residue that is incorporated into the soil (i.e., the portion of the crop that has been neither removed from the field as crop nor burned). To estimate state emissions of N_2O from crop residues (for both N-fixing and non-N-fixing crops), two steps should be performed: (1) obtain data on production of crops and (2) calculate the amount of nitrogen entering the crop residue pool.

Step (1) Obtain Required Data

- *Required Data*. In order to estimate N_2O emissions from crop residue, data on state crop production of both N-fixing (e.g., beans and pulses) and non-N-fixing crops (e.g., wheat and corn) are needed.

- *Data Sources*. Departments within each state responsible for agricultural research should be consulted first. Crop production information is provided by USDA and is available on the Internet at http://www.usda.gov/nass/pubs/histdata.htm.

- *Units for Reporting Data*. The production of crops should be reported in kg biomass/yr.

Step (2) Calculate the Amount of Nitrogen Entering the Crop Residue Pool

Little data exists on the amount of crop residue left on fields, because crop residue is not recorded as a commercial product. For example, during the harvest of corn, typically only the kernels are taken from the field and other parts of the corn plant (i.e., stalks and cobs) are shredded and left on the field as crop residue. Following the methodology used in the U.S. greenhouse gas inventory (U.S. EPA 1998), it was assumed that all residues from corn, wheat, bean, and pulse production, except the fractions burned in the field after harvest, are left in the field (e.g., plowed under).

To estimate the total nitrogen in crop residues returned to the soil for each crop, multiply crop production by (1) the mass ratio of crop residue to crop, and (2) the dry matter fraction for aboveground biomass. The resulting values are the amounts of crop residue biomass, measured as dry matter. Next, multiply by (1) a factor of 1 minus the fractions burned, used as fuel, used in construction, and/or used as fodder; and (2) the nitrogen content of the residue. These steps are shown in the equation below.

$$\begin{array}{c} \text{Total Nitrogen} \\ \text{in Crop} \\ \text{Residues} \\ \text{Returned to} \\ \text{Soils} \\ \text{(kg N/yr)} \end{array} = \begin{array}{c} \text{Crop} \\ \text{Production} \\ \text{(kg)} \end{array} \text{ x } \begin{array}{c} \text{Mass} \\ \text{Ratio of} \\ \text{Crop} \\ \text{Residue to} \\ \text{Crop} \end{array} \text{ x } \begin{array}{c} \text{Dry} \\ \text{Matter} \\ \text{Fraction} \\ \text{for} \\ \text{Above-} \\ \text{ground} \\ \text{Biomass} \end{array} \text{ x } \begin{array}{c} \text{(1-Fraction} \\ \text{Burned –} \\ \text{Fraction} \\ \text{Used as} \\ \text{Fuel –} \\ \text{Fraction} \\ \text{used in} \\ \text{Construc-} \\ \text{tion –} \\ \text{Fraction} \\ \text{used as} \\ \text{Fodder)} \end{array} \text{ x } \begin{array}{c} \text{N Content of} \\ \text{Aboveground} \\ \text{Biomass (kg} \\ \text{N/kg dry} \\ \text{biomass)} \end{array}$$

Table 9.4-2 Residue to Crop Mass Ratio, Residue Dry Matter Fraction, Fraction Burned, and Residue Nitrogen Content for Selected Crops

Crop	Residue to Crop Mass Ratio	Residue Dry Matter Fraction	Fraction Burned	N Content of Residue (kg N/kg dry biomass)
Corn for Grain	1	0.4	0.03	0.0094
All Wheat	1.3	0.83	0.03	0.0058
Soybeans for Beans	2.1	0.86	0.03	0.03
Peanuts for Nuts	1	0.90	0.03	0.03
Dry Edible Beans	2.1	0.86	0	0.03
Dry Edible Peas	1.5	0.87	0	0.03
Austrian Winter Peas	1.5	0.87	0	0.03
Lentils	2.1	0.86	0	0.03
Wrinkled Seed Peas	1.5	0.87	0	0.03
Sources: Strehler and Stützle 1987, Barnard and Kristoferson 1985, and U.S. EPA 1998.				

4.1.5 PRODUCTION OF NITROGEN-FIXING CROPS

N_2O is also emitted from the cultivation of N-fixing crops, also known as legumes. To estimate state emissions of N_2O from N-fixing crops, two steps should be performed: (1) obtain required data on biomass production of N-fixing crops and (2) calculate total nitrogen input from N-fixing crops.

Step (1) Obtain Required Data

- *Required Data*. In order to estimate N_2O emissions from the cultivation of legumes, data on the amount of beans, pulses, and alfalfa produced in the state are needed.

- *Data Sources*. Departments within each state responsible for agricultural research should be consulted first. Crop production information on soybeans, peanuts, dry edible beans and peas, Austrian winter peas, lentils, alfalfa, and wrinkled seed peas. is provided by USDA and is available on the Internet at http://www.usda.gov/nass/pubs/histdata.htm. Hard copy information is also available through USDA's publication, *Field Crops: Final Estimates* (USDA 1994). Estimates of production of forage legumes such as red clover, white clover, birdsfoot trefoil, arrowleaf clover, crimson clover, and hairy vetch might be obtained through consultation with state agricultural research agents.

- *Units for Reporting Data*. The production of legumes should be reported in kg dry biomass/yr. If production figures for N-fixing crops are not available as dry biomass, multiply the production figure by a factor of (1 - 0.15), or 0.85, to account for crop water content.[9]

[9] The fraction of crop water content varies by crop. The value provided here is presented as a default conversion factor in the *Revised 1996 Guidelines* (IPCC 1997). Where available, crop-specific values may be used.

Step (2) Calculate Total Nitrogen Input from N-fixing Crops

In order to calculate the total nitrogen input from N-fixing crops, multiply (a) the production of pulses and soybeans in the state times (b) one plus the mass ratio of residue to product times (c) the fraction of dry matter in aboveground biomass times (d) the fraction of nitrogen in the crops. Total crop biomass is estimated as given below because, in accordance to IPCC Good Practice recommendation, the method assumes that the ratio of residue to crop product will vary according to crop type, and in the case of legumes used as fodder it approaches zero (IPCC 1999). The IPCC method uses the fraction of nitrogen in N-fixing crops as a proxy for the amount of nitrogen added to soil by N-fixing crops (IPCC 1997). The default value is shown below:

- Fraction of nitrogen in N-fixing crops = 0.03 kg N/kg of dry biomass (IPCC 1997).

Nitrogen input from N-fixing crops is calculated as follows:

Nitrogen Input from N-fixing Crops (kg N/year)	=	Production of N-fixing Crops in State (kg dry biomass/year)	x	1 + Residue to Crop Product Mass Ratio	x	Fraction of Dry Matter in Aboveground Biomass	x	Fraction of Nitrogen in N-fixing Crops (kg N/kg dry biomass)

The values are then summed across all crops, to yield the total nitrogen input from N-fixing crops.

Total Direct N_2O Emissions Excluding Cultivation of Histosols

Using the results of equations found in Sections 4.1.1 through 4.1.5, fill in Column A of Table 9.4-3. Multiply the amount of N input for each row in Table 9.4-3 by 0.0125, the default emission factor for direct soil emissions to yield direct soil emissions of N_2O in terms of nitrogen (IPCC 1997). Sum the direct soil emissions and enter the total in the bottom row of Column C.

Table 9.4-3. Worksheet to Calculate Direct N_2O Emissions Excluding Histosols

Source of N	**A** **Amount of N Input (kg N/yr)**	**B** **Emission Factor for Direct Emissions (kg N_2O-N/kg N)**	**C** **Direct Soil Emissions (kg N_2O-N/yr)** C = A x B
Unvolatilized Applied N from Synthetic Fertilizer (kg N/yr)		0.0125	
Unvolatilized Applied N from Synthetic Fertilizer when applied to fields w/ Organic Fertilizer (kg		0.025	
Unvolatilized Applied N from Organic Fertilizers (kg N/yr)		0.0125	
Unvolatilized Applied N from Daily Spread Operations (kg N/yr)		0.0125	
N in Crop Residues Returned to Soils (kg N/yr)		0.0125	
N Fixation from N-Fixing Crops (kg N/yr)		0.0125	
Subtotal			

4.1.6 CULTIVATION OF HIGH ORGANIC CONTENT SOILS

N_2O is also emitted from the cultivation of high organic content soils, or histosols. To estimate state emissions of N_2O from the cultivation of histosols, two steps should be performed: (1) obtain required data on histosol cultivation and (2) calculate direct N_2O emissions from histosols.

Step (1) Obtain Required Data

- *Required Data*. The emissions of N_2O from the cultivation of histosols can be estimated using the area of cultivated histosols in the state.
- *Data Sources*. Departments within each state responsible for agricultural research should be consulted first. Mausbach and Spivey (1993) compiled an estimate of the national area of cultivated histosols. This estimate does not provide a breakdown to the state level; therefore, states may have difficulty locating data on histosol cultivation.
- *Units for Reporting Data*. The area of cultivated histosols in the state should be reported in hectares.[10] The emissions factor, where available, should be expressed in kg N_2O-N/ha/yr of cultivated histosol.

Step (2) Estimate the Direct N_2O Emissions from Cultivation of Histosols

Multiply the area of cultivated soils times the emission factor for direct emissions from histosols to determine direct emissions from this source, as shown in Table 9.4-4. According to the IPCC, the emission factor for direct emissions from histosols ranges from 5 to 10 kg N_2O-N/ha/yr, depending on climate (IPCC 1997). The U.S. inventory (U.S. EPA 1998) estimates emissions from histosols using the low end of this range, which corresponds to temperate climates and would be appropriate for most, if not all states.

Table 9.4-4. Worksheet to Calculate Direct N_2O Emissions from Cultivation of Histosols

Source of Direct Emissions	**A** **Area of Cultivated Histosols (ha)**	**B** **Emission Factor for Direct Soil Emissions (kg N_2O-N/ha-yr)**	**C** **Direct Emissions from Histosols (kg N_2O-N/yr)**
		8	C = A x B
Histosols			

[10] To convert from acres to hectares, multiply acres times a conversion factor of 0.4047.

4.1.7 CALCULATE TOTAL DIRECT N_2O EMISSIONS FROM AGRICULTURAL CROPPING PRACTICES

Table 9.4-5 presents a worksheet for calculating the total direct N_2O emissions from agricultural soils. Direct soil emissions expressed in terms of nitrogen need to be multiplied by 44/28 to convert to units of N_2O.

Table 9.4-5. Worksheet to Calculate Total Direct N_2O Emissions from Agricultural Cropping Practices

Source of Direct Emissions	**A** **Direct Soil Emissions (kg N_2O-N/yr)**	**B** **Total Direct Emissions of N_2O (kg N_2O/yr)**
		B = A x (44/28)
Unvolatilized Applied N from Synthetic Fertilizer, Organic Fertilizers, and Daily Spread Operations; N in Crop Residues Returned to the Soil, and N-Fixation by Legumes (From Table 9.4-3)		
Histosols (From Table 9.4-4)		
Subtotal		

4.2. DIRECT N_2O EMISSIONS FROM ANIMAL PRODUCTION

This section provides a method for determining direct N_2O emissions from animal excretion deposited directly onto pasture, range, and paddock.

Step (1) Obtain Required Data

- *Required Data*. The information needed to estimate direct N_2O emissions from animal waste deposited directly onto pasture, range, and paddock are data, for each type of animal, on (1) animal population, (2) typical animal mass (TAM), (3) Kjeldahl nitrogen[11] emitted per unit of animal mass, and (4) the percent of manure deposited on pasture, range, and paddock.

- *Data Source*. Departments within each state responsible for conducting agricultural research and monitoring agricultural waste practices should be consulted for animal population data. Alternatively, animal population data are provided by the National Agriculture Statistics Service of the U.S. Department of Agriculture (USDA) and can be found at the following Internet address: http://usda.mannlib.cornell.edu/cgi-usda/agency.cgi?nass. Animal population data may also be found in the *Census of Agriculture, Volume 1: Geographic Area Series*, published by the Bureau of the Census. Table 9.4-1 provides default average TAM and total Kjeldahl nitrogen excreted per unit mass for each of the animal types. The percent of manure for each animal type deposited on pasture, range and paddock can be found in Chapter 7, Tables 7.4-2 to 7.4-10. Where state data are available, they may be used in place of these default values.

- *Units for Reporting Data*. Animal populations should be reported in number of head.

[11] Total Kjeldahl nitrogen is a measure of organically bound nitrogen and ammonia nitrogen.

Step (2) Calculate Nitrogen from Animal Waste Deposited Directly on Pasture, Range, and Paddock

For each animal type *i*, multiply population times (1) the percent of manure deposited on pasture, range, and paddock (from Tables 7.4-2 through 7.4-10); (2) the typical animal mass for animal type *i* (found in Table 9.4-1); and (3) the daily rate of nitrogen excreted by animal type *i* (also found in Table 9.4-1). Use these data to perform the calculation shown below, for each animal type. Then sum the results across all animal types to determine total nitrogen input from animal waste deposited on pasture, range, and paddock.

Total Kjeldahl N Excreted by Animal Type$_i$ (kg/yr)	=	Population of Animal Type$_i$ (head)	x	Percent of Manure Deposited on Pasture, Range, and Paddock for Animal Type$_i$	x	(TAM (kg) /1000)	x	Kjeldahl N per day per 1000 kg mass (kg/day)	x	365 (days/yr)

The total Kjeldahl nitrogen excreted per year needs to be adjusted to account for the portion that volatilizes to NH_3 and NO_x, i.e., 0.20 (IPCC 1997). To do so, multiply the product of the equation above times (1 - 0.20), or 0.80, as shown in the equation below.

Unvolatilized Applied N from Waste Deposited on Pasture, Range, and Paddock (kg N)	=	Total Kjeldahl N Excreted (kg/yr)	x	0.80

For an example of this methodology, see the example provided in Section 4.1.3 and replace the percent of manure managed as daily spread with the percent deposited directly on pasture, range, and paddock.

Step (3) Calculate Direct N_2O Emissions from Animal Production

The direct N_2O emissions from animal production can be calculated by multiplying the unvolatilized applied nitrogen from animal waste deposited on pasture, range, and paddock by the IPCC default emission factor, 0.02kg N_2O-N/kg N excreted (IPCC 1997).

Total Direct N_2O Emissions from Animal Production (kg N_2O-N)	=	Unvolatilized Applied N from Waste Deposited on Pasture, Range, and Paddock (kg N)	x	Emission Factor for Direct Emissions (kg N_2O-N/kg N excreted)

Total direct N_2O emissions from animal production in terms of nitrogen must then be multiplied by 44/28 to convert to units of N_2O.

Table 9.4-6. Worksheet to Calculate Total Direct N_2O Emissions from Animal Production

Source of Direct Emissions	A Direct Soil Emissions (kg N_2O-N/yr)	B Total Direct Emissions of N_2O (kg N_2O/yr)
		B = A x (44/28)
Direct N_2O Emissions from Animal Production		

4.3. INDIRECT N_2O EMISSIONS FROM NITROGEN APPLIED TO AGRICULTURAL SOILS

N_2O emissions can also result from agricultural activities via the following indirect pathways:

- NH_3 and NO_x volatilization; and
- Leaching and runoff of nitrogen from agricultural fields.

(Another indirect pathway for N_2O to enter the atmosphere is through sewage sludge; the methodology for estimating emissions from this source is presented in Chapter 12 of this volume.)[12]

4.3.1 NO_X AND NH_3 VOLATILIZATION

Some of the nitrogen applied to the soil as fertilizer and excreted by livestock volatilizes, enters the atmosphere as NO_x and NH_3, and subsequently returns to soils through atmospheric deposition, thereby enhancing N_2O production. The atmospheric deposition of NO_x and NH_3 can be calculated in three steps: (1) obtain required data; (2) calculate the amount of N applied to the soil as fertilizer that volatilizes;[13] and (3) calculate total nitrogen excretion by livestock that volatilizes. These steps are described below.

Step (1) Obtain Required Data

- *Required Data*. The estimates for indirect emissions through atmospheric deposition are based on the amount of nitrogen in fertilizer and total animal waste that is applied or deposited on the soil. The activity data used in Sections 4.1.1, 4.1.2, 4.1.3, and 4.2 are required to determine the amount of nitrogen that volatilizes.

- *Data Sources*. Use activity data obtained for sections 4.1.1, 4.1.2, 4.1.3, and 4.2.[14]

---

[12] The IPCC allocates emissions from this source to the Waste Chapter of the *Revised 1996 Guidelines*, as well (IPCC 1997).

[13] The methodology for estimating nitrogen applied to the soil as fertilizer that volatilizes accounts for all commercially sold fertilizer (both synthetic and organic) minus the manure fraction of commercially sold fertilizer. All volatilization from animal wastes are accounted for in Step (3).

[14] States interested in directly measured wet and dry atmospheric deposition data can access the National Atmospheric Deposition Program (NADP) on the Internet at http://nadp.sws.uiuc.edu/ for wet N deposition data, and the EPA Clean Air Status and Trends Network (CASTNet) Internet site at http://www.epa.gov/acidrain/castnet/getdata.html for dry N deposition data. These resources report data collected at various monitoring stations across the U.S. In addition, the USGS National Water Quality Assessment Program's

- *Units for Reporting Data*. Data on synthetic fertilizer application, organic fertilizer application, and nitrogen excretion should be reported in kg N per year.

Step (2) Calculate the Amount of N Applied to the Soil as Fertilizer that Volatilizes

In order to calculate NH_3 and NO_x volatilization from fertilizer application, multiply the amount of nitrogen applied to the soil times the fraction of fertilizer nitrogen that volatilizes. The IPCC suggests default values of 10 and 20 percent for the fraction of synthetic and organic fertilizer N that volatilizes, respectively (IPCC 1997). See the following equations:

Volatilized N from Synthetic Fertilizer Application (kg N/year)	=	Total Application of Synthetic Fertilizer in the State (kg N/year) (See Section 4.1.1, "Step (2)")	x	Fraction of Synthetic Fertilizer N Applied that Volatilizes
Volatilized N from Organic Fertilizer Application (kg N/year)	=	Total Application of Organic Fertilizer in the State (kg N/year) (See Section 4.1.2, "Step (2)")[15]	x	Fraction of Organic Fertilizer N Applied that Volatilizes
Volatilized N from Fertilizer Application (kg N/year)	=	Volatilized N from Synthetic Fertilizer Application (kg N/year)	+	Volatilized N from Organic Fertilizer Application (kg N/year)

Step (3) Calculate the Total Nitrogen Excretion by Livestock that Volatilizes

NH_3 and NO_x volatilization from animal wastes can be calculated using total nitrogen excretion by all livestock in the state. In order to calculate total nitrogen excretion, use the equation below, which is a variation on the equations provided in Sections 4.1.3 and 4.2.

Total Kjeldahl N Excreted (kg/year)	=	Population of Animal Type$_i$ (head)	x	TAM (kg) /1000	x	Kjeldahl N (kg/day) per 1000 kg mass	x	365 days/ year

Nitrogen excreted as calculated above must then be summed across animal types. The total nitrogen excretion by livestock should then be multiplied by 20 percent, the fraction of total manure nitrogen that volatilizes, as shown in the following equation (IPCC 1997).

Total N Excretion by Livestock that Volatilizes (kg N/year)	=	Total N Excretion by Livestock (kg N/year)	x	Fraction of Total Manure N Excreted that Volatilizes

report *on Nonpoint and Point Sources of Nitrogen in Major Watersheds of the United States* (Internet address: http://wwwrvares.er.usgs.gov/nawqa/WRI94-4001.html) contains estimates of atmospheric deposition of nitrogen in regions of the U.S., based on data collected at watersheds across the country.

[15] Note that this factor should only include organic fertilizers *other than* manure.

Step (4) Calculate Total Indirect N_2O Emissions from Volatilization to NH_3 and NO_x

Using the totals calculated in Steps 2 and 3, calculate the indirect emissions from both sources of atmospheric deposition. Sum the amount of synthetic N applied to soil that volatilizes and the total N excretion by livestock that volatilizes, and multiply by 0.01 kg N_2O-N per kg NH_3-N and NO_x-N (where 0.01 is the emission factor for indirect emissions, from IPCC 1997). This method accounts for the fraction of volatized N returned to the soils and then emitted as N_2O. See Table 9.4-7.

Table 9.4-7. Worksheet for Calculating Indirect N_2O Emissions Resulting from Volatilization to NH_3 and NO_x

Sources of Indirect Emissions	A Total Amount of N that Volatilizes (kg NH_3-N + NO_x-N/kg N)	B Emission Factor (kg N_2O-N/kg NH_3-N + NO_x -N)	C N_2O Emissions (kg N_2O-N/yr)
		0.01	C = (A x B) x 10^{-6}
Fertilizer		0.01	
Livestock Excretion		0.01	
Subtotal			

4.3.2 Leaching and Runoff of Nitrogen from Agricultural Fields

The estimates for N_2O emissions from leaching and runoff from agricultural soils account for nitrogen applied to soils that migrates into groundwater, rivers, and estuaries. Emissions of N_2O from leaching and runoff can be calculated using the following two steps.

Step (1) Obtain Required Data

- *Required Data*. Estimates of N_2O emissions from leaching and runoff are based on the amount of nitrogen in fertilizer and total animal waste that is applied or deposited on the soil. The amount of unvolatilized nitrogen from commercial synthetic and organic fertilizers calculated in Section 4.1.1, Step 2, and Section 4.1.2, Step 2 can be used here.[16] The activity data used in Sections 4.1.3 and 4.2 provide the basis for the calculation in Step 3 of this section.

- *Data Sources*. Use activity data and results presented in Sections 4.1.1, 4.1.2, 4.1.3, and 4.2.[17]

- *Units for Reporting Data*. Data on unvolatilized synthetic fertilizer application, organic fertilizer application, and nitrogen excretion should be reported in kg N per year.

[16] Where a state's commercial organic fertilizer data includes some manure, the unvolatilized nitrogen from commercial organic fertilizer must be recalculated to reflect only non-manure commercial organic fertilizer application. This is to avoid double counting indirect emissions from manure.

[17] States interested in obtaining directly measured data on nitrogen in specific watersheds should refer to the USGS National Water Quality Assessment Program's report *on Nonpoint and Point Sources of Nitrogen in Major Watersheds of the United States* (Internet address: http://wwwrvares.er.usgs.gov/nawqa/WRI94-4001.html).

Step (2) Estimate Leaching and Runoff from Fertilizer Application

Indirect N_2O emissions from leaching and runoff can be calculated by using the default ratio provided below.

- Fraction of N that leaches or runs off = 0.3 kg N/kg N in fertilizer or manure (IPCC 1997).

The methodology for estimating leaching and runoff from non-manure fertilizer application is shown in the equations below.

For Synthetic Fertilizer:

N Leaching and Runoff from Synthetic Fertilizer (kg N/yr)	=	Unvolatilized Applied N from Synthetic Fertilizer (kgN/yr)	x	0.3 (i.e., Fraction of Unvolatilized N that Leaches or Runs Off)

For Organic Fertilizer:

N Leaching and Runoff from Organic Fertilizers (kg N/yr)	=	Unvolatilized Applied N from Organic Fertilizer (kg N/yr)	x	0.3 (i.e., Fraction of Unvolatilized N that Leaches or Runs Off)

The results of these two equations should be summed to yield total N from leaching and runoff from fertilizer application.

Step (3) Estimate Leaching and Runoff from Animal Waste

Animal waste also contributes to N_2O emissions from leaching and runoff. Use the following emission factor and the equation below to estimate nitrogen leaching from animal waste. Note that the input to this equation, “Total N Excretion by Livestock,” can be found in the equation under “Step 3” of Section 4.3.1.

- Fraction of N that leaches or runs off = 0.3 kg N/kg N in fertilizer or manure (IPCC 1997); and
- Fraction of total manure N excreted that volatilizes = 0.2 kg N/kg N (IPCC 1997).

N Leaching and Runoff from Excretion by Livestock (kg N/year)	=	Total N Excretion by Livestock (kg N/yr)	x	0.80 (i.e., Fraction of Total Synthetic Fertilizer N Not Volatilized as NO_x and NH_3)	x	0.3 (i.e., Fraction of Unvolatilized N that Leaches or Runs Off)

Step (4) Estimate Total Indirect Emissions from Leaching and Runoff

Emissions from leaching and runoff are comprised of leached nitrogen from fertilizers (synthetic and organic) and animal waste. The results of steps (2) and (3) above must be multiplied by the emissions factor for indirect N_2O emissions, to yield total indirect N_2O emissions from leaching. These equations are diagramed below.

- Emission factor for emissions of N_2O through leaching/runoff = 0.025 kg N_2O-N/kg N leaching/runoff (IPCC 1997).

$$\text{Total N Leaching (kg N/year)} = \text{N Leaching and Runoff from Synthetic Fertilizer (kg N/year)} + \text{N Leaching and Runoff from Organic Fertilizers (kg N/year)} + \text{N Leaching and Runoff from Excretion by Livestock (kg N/year)}$$

$$\text{Total } N_2O \text{ Emissions from Leaching and Runoff (kg } N_2O\text{-N/yr)} = \text{Total N Leaching (kg N/yr)} \times 0.025 \text{ (i.e., Emission Factor for Emissions of } N_2O \text{ through Leaching/Runoff) (kg } N_2O\text{-N/kg N)}$$

4.3.3 CALCULATE TOTAL INDIRECT N_2O EMISSIONS FROM AGRICULTURAL SOILS

Table 9.4-8 presents a worksheet for calculating the total indirect N_2O emissions from agricultural soils. Total direct N_2O emissions from animal production in terms of nitrogen must be multiplied by 44/28 to convert to units of N_2O.

Table 9.4-8. Worksheet for Calculating Indirect N_2O Emissions from Agricultural Soils

Source of Indirect Emissions	**A** **Indirect Soil Emissions (kg N_2O-N/yr)**	**B** **Total Indirect N_2O Emissions (kg N_2O/yr)**
		B = A x (44/28)
Atmospheric Deposition		
Leaching/Runoff		
Subtotal		

4.4 CALCULATE TOTAL N_2O EMISSIONS FROM AGRICULTURAL SOILS

Table 9.4-9 presents a worksheet for calculating the total emissions (direct and indirect) of N_2O from agricultural soils. To convert the estimate of N_2O emissions in units of kilograms (as calculated in Table 9.4-9) to units of metric tons of carbon equivalent (MTCE), first convert kilograms to metric tons by dividing the number of kilograms by 1000. Then multiply the number of metric tons of N_2O times (1) a factor of 310 (the GWP for N_2O) and (2) 12/44 (the ratio of the atomic weight of carbon to the molecular weight of CO_2). The resulting value represents N_2O emissions in MTCE.

Table 9.4-9. Worksheet to Calculate the Total Emissions of N_2O from Agricultural Soils

Type of Emission	**A.** **Total N_2O Emissions (kg N_2O/yr)**	**B.** **Total N_2O Emissions from Agricultural Soils (MTCE)**
		B = (A x 310 x 12/44)/1000
Direct Emissions from Agricultural Cropping Practices (in Table 9.4-5) + Direct Emissions from Animal Production (in Table 9.4-6)		
Indirect (Subtotal in Table 9.4-8)		
TOTAL		

4.5 CO_2 FROM AGRICULTURAL APPLICATION OF LIME

Step (1) Obtain Required Data

- *Required Data.* The data required are the amounts of each type of lime used for agriculture in the state: (1) limestone (calcite), and (2) dolomite.

- *Data Source.* In-state sources, such as state agriculture departments, should be consulted first. State-specific resources and contacts can be found on the Internet at http://minerals.er.usgs.gov/minerals/pubs/state/index.html#contact.
  Additionally, agricultural lime consumption by state may be found in the publication *Crushed Stone: Annual Report* (U.S. Geological Survey), available on the Internet at http://minerals.er.usgs.gov/minerals/pubs/commodity/stone_crushed/. Under the Minerals Yearbook bullet on this page, click on the pdf file for the year desired. In this publication, the table *Crushed Limestone and Dolomite Sold or Used by Producers in [Year], By State and Use* (Table 15 in the 1996 Report) has data on the quantity of limestone and dolomite used for agriculture. To estimate the breakdown between limestone and dolomite use for agriculture, use the percentages of total limestone and dolomite used in the state, from the table *Crushed Limestone and Dolomite Sold or Used by Producers in the United States in [Year], By State* (Table 8 in the 1996 Report). If the state percentages are not available, use the national percentages from the “total” row of the same table.

  If the report *Crushed Stone: Annual Report* is used, note that a significant portion of limestone and dolomite use is often unspecified. The amount of unspecified limestone or dolomite used for agriculture in a state may be estimated by assuming that the proportion of the U.S. total *unspecified* limestone or dolomite used by the state for agriculture equals the proportion of the U.S. total *specified* limestone or dolomite use that is used by the state for agriculture. This approach is suggested because data for the former proportion are unavailable. To estimate the amount of unspecified limestone use that is used for agriculture, first determine the ratio of (1) the state’s specified agricultural limestone use to (2) the U.S. total *specified* limestone use. Multiply this ratio by the U.S. total for *unspecified* limestone use. This will yield an estimate of the amount of unspecified limestone use in the U.S. that is used for agriculture in the state. Repeat the procedure for dolomite use. Total agricultural limestone and dolomite use in the state will thus be the amounts specified, plus the amounts estimated as described in this paragraph.

Finally, if lime application data for the state fluctuates significantly from year to year, take the average of application data for the years immediately preceding the inventory year (e.g., for a 1990 inventory, average lime application data for 1988, 1989, and 1990).

- *Units for Reporting Data.* Annual agricultural consumption of limestone and dolomite should be supplied in metric tons. If the data source presents data in short tons, multiply by .907 to convert to metric tons.

Example	According to the *Crushed Stone: Annual Report* (1995), the total specified use of limestone for agriculture in Michigan in 1995 was approximately **132,000 metric tons.**

Step (2) Estimate CO_2 Emissions from Agricultural Use of Lime

Depending on the type of lime applied, multiply the amount of lime consumed by the appropriate emissions factor: (1) 0.12 for limestone (calcite) and (2) 0.130 for dolomite (IPCC, 1997). The product of this equation will yield metric tons of carbon applied to the soil in the form of lime. Next, multiply the amount of carbon emitted by 44/12 to obtain the amount of carbon dioxide emitted.[18]

a) Limestone - *Calcite* ($CaCO_3$)

$$\text{Total } CO_2 \text{ Emissions (metric tons)} = \text{Limestone Used for Agriculture (metric tons)} \times 0.12 \text{ metric tons C/metric ton Limestone (Calcite)} \times 44/12\ CO_2/C$$

b) Dolomite ($CaMg(CO_3)_2$)

$$\text{Total } CO_2 \text{ Emissions (metric tons)} = \text{Limestone Used for Agriculture (metric tons)} \times 0.13 \text{ metric tons C/metric ton Dolomite} \times 44/12\ CO_2/C$$

[18] Although liming leads to emissions over a period of several years, the accounting method attributes emissions to the year in which the lime is applied. Additionally, some fraction of the carbon loading from liming leaches to ground water, but this fate is not addressed in the methodology; all of the carbonate is assumed to be converted to gaseous CO_2.

Example To determine the amount of unspecified limestone and dolomite used for agriculture in Michigan in 1995:

Limestone (Calcite)

Total limestone use in U.S. in 1995 = 804,000,000 metric tons

Total unspecified limestone use in U.S. in 1995 = 302,000,000 metric tons

Total specified limestone use in U.S. in 1995 = 804,000,000 – 302,000,000 metric tons = 502,000,000 metric tons

Ratio of limestone used for agriculture in Michigan to total specified limestone use in U.S.:
113,500 metric tons /502,000,000 metric tons = .000226

Amount of U.S. total unspecified limestone used for agriculture in Michigan :

302,000,000 metric tons x .000226 = **68,300 metric tons of limestone**

Dolomite

Total dolomite use in U.S. in 1995 = 93,100,000 metric tons

Total unspecified dolomite use in U.S. in 1995 = 25,850,000 metric tons

Total specified dolomite use in 1995 in U.S. = 93,100,000 – 25,850,000 metric tons = 67,250,000 metric tons

Ratio of dolomite used for agriculture in Michigan to total specified dolomite use in U.S.:

32,000 metric tons /67,250,000 metric tons = 0.000476

Amount of U.S. total unspecified dolomite used for agriculture in Michigan:

25,850,000 metric tons x 0.000476 = **12,300 metric tons of dolomite**

Example To estimate the amount of limestone and dolomite used in agriculture in Michigan in 1995, add the unspecified use (derived above) to the specified use as shown here:

113,500 metric tons of agricultural uses of limestone in specified uses + 68,300 metric tons of agricultural uses of limestone in unspecified uses = **181,800 metric tons of limestone**
32,000 metric tons of agricultural uses of dolomite in specified uses + 12,300 metric tons of agricultural uses of dolomite in unspecified uses = **44,300 metric tons of dolomite**

Example To calculate Total CO_2 Emissions from agricultural use of lime in Michigan in 1995,

Calcite

181,800 metric tons limestone x 0.12 metric tons C/metric ton limestone (calcite) x 44/12 CO_2/C

= **80,000 metric tons CO_2**

Dolomite

44,300 metric tons dolomite x 0.130 metric tons C/ metric ton dolomite x 44/12 CO_2/C

= **21,100 metric tons CO_2**

Step (3) Sum the Results of Steps 2a and 2b to Obtain Total Emissions

Total CO_2 Emissions from Agricultural Use of Limestone (metric tons)	=	Total CO_2 from Agricultural Use of Limestone (Calcite) (metric tons CO_2)	+	Total CO_2 from Agricultural Use of Dolomite (metric tons CO_2)

Example To calculate Total CO_2 Emissions from Agricultural Use of Limestone in Michigan in 1995:

80,000 metric tons CO_2 from limestone (calcite) + 21,100 metric tons CO_2 from dolomite = **101,100 metric tons CO_2**

Step (4) Convert Tons of CO_2 Emissions to Metric Tons of Carbon Equivalent

To estimate CO_2 emissions in units of MTCE, multiply the tons of CO_2 calculated in Step 3 above times (1) a factor of 1 (the GWP for CO_2) and (2) 12/44 (the ratio of the atomic weight of carbon to the molecular weight of CO_2).

5

ALTERNATE METHODS FOR ESTIMATING EMISSIONS

No alternate methods have yet been approved by the Greenhouse Gas Committee of the Emission Inventory Improvement Program.

6

QUALITY ASSURANCE/QUALITY CONTROL

Quality assurance (QA) and quality control (QC) are essential elements in producing high quality emission estimates and should be included in all methods to estimate emissions. QA/QC of emissions estimates are accomplished through a set of procedures that ensure the quality and reliability of data collection and processing. These procedures include the use of appropriate emission estimation methods, reasonable assumptions, data reliability checks, and accuracy/logic checks of calculations. Volume VI of this series, *Quality Assurance Procedures*, describes methods and tools for performing these procedures.

Scientific knowledge is limited regarding N_2O production and emissions from soils to which nitrogen is added via fertilizers, daily spread operations, crop residues, or nitrogen-fixing crops. For example, for fertilizer alone significant uncertainties exist regarding the agricultural practices, soil properties, climatic conditions, and biogenic processes that determine how much fertilizer nitrogen various crops absorb, how much remains in soils after fertilizer application, and in what ways the remaining nitrogen evolves into N_2O, nitrogen gas (N_2), and other nitrogen compounds.

A major difficulty in estimating the magnitude of emissions from agricultural soil management has been the relative lack of emissions measurement data across a suitably wide variety of controlled conditions, making it difficult to develop statistically valid estimates of emission factors. For example, attempts have been made to develop emission factors for different fertilizer and crop types for the purposes of developing state and national emission inventories. However, the accuracy of these emission factors has been questioned. For example, while some studies indicate that N_2O emission rates are higher for ammonium-based fertilizers than for nitrate, other studies show no particular trend in N_2O emissions related to fertilizer types (see Eichner (1990) and Bouwman (1990) for reviews of the literature). Therefore, it is possible that fertilizer type is not the most important factor in determining emissions. One study suggests that N_2O emissions from the nitrification of fertilizers may be more closely related to soil properties than to the type of fertilizer applied (Byrnes *et al*., 1990).

While it is relatively well known how the natural processes individually affect N_2O emissions, it is not well understood how the interaction of the processes affects N_2O emissions. Experiments have shown that in some cases increases in each of the following factors (individually) enhance N_2O emissions: pH, soil temperature, soil moisture, organic carbon content, and oxygen supply (Bouwman, 1990; Eichner, 1990). However, the way in which several factors—e.g., soil moisture, organic carbon content, and microbial population—may together affect N_2O emissions, is not readily predictable.

N_2O may also be emitted from surface and ground water, due to nutrient leaching and runoff from agricultural systems. Methods to estimate emissions of N_2O from these sources are included, however, data and emission coefficients are relatively uncertain at this time. Because of the potential relative importance of these N_2O emissions, they should be included using the currently available methodologies and using revised methodologies as data availability and scientific understanding permit.

Uncertainties in estimates of CO_2 emissions from limestone application arise from three principal sources. First, variations in the chemical composition of limestone result in uncertainty in the emission factor. In addition to calcite, limestone may contain smaller amounts of magnesia, silica, and sulfur. Second, data on the amount of limestone used in agriculture are incomplete, because not all uses of limestone are specified. Many crushed stone producers do not report a breakdown by end-use, so the total uses of the crushed limestone they produce is reported as unspecified. Applying the percentage of agricultural use of crushed stones, however, provides a fair estimation of the amount of unspecified crushed stone used for agriculture (Tepordei, 1995). Third, and perhaps most importantly, much of the carbon produced in the decomposition of limestone is probably in the form of dissolved species (H_2CO_3, HCO_3^-, CO_3^{-2}) that partition to ground water, rather than volatilizing as CO_2. This method assumes all of the carbon is converted to CO_2.

6.1 DATA ATTRIBUTE RANKING SYSTEM (DARS) SCORES

DARS is a system for evaluating the quality of data used in an emission inventory. To develop a DARS score, one must evaluate the reliability of eight components of the emissions estimate. Four of the components are related to the activity level (e.g., the amount of nitrogen added to the soil). The other four components are related to the emission factor (e.g., the amount of N_2O emitted per kilogram of nitrogen added to the soil). For both the activity level and the emission factor, the four attributes evaluated are the measurement method, source specificity, spatial congruity, and temporal congruity. Each component is scored on a scale of zero to one, where one represents a high level of reliability. To derive the DARS score for a given estimation method, the activity level score is multiplied by the emission factor score for each of the four attributes, and the resulting products are averaged. The highest possible DARS composite score is one. A complete discussion of DARS may be found in Chapter 4 of Volume VI, *Quality Assurance Procedures*.

The DARS scores provided here are based on the use of the emission factors provided in this chapter, and activity data from the U.S. government sources referenced in the various steps of the methodology. If a state uses state data sources for activity data, the state may wish to develop a DARS score based on the use of state data.

Table 9.6-1
DARS Scores: Direct N_2O Emissions from Agricultural Soils

DARS Attribute Category	Emission Factor Attribute	Explanation	Activity Data Attribute	Explanation	Emission Score
Measurement	3	Since the factor is derived from field measurements, applying the DARS formula the score would be 5. However, emissions vary across soil types, climates, and management practices.	6	The value of 6 is a composite value, based on use of top-down statistics for fertilizer purchases; estimates of manure use based on sample data; estimates of nitrogen from crop residues based on crop production; and estimates of histosol area cultivated.	0.18
Source Specificity	7	The emission factor was developed specifically for N_2O from fertilizer use, but not for emissions from legume cultivation, crop residue incorporation, or manure application. Variability is expected to be low to moderate.	9	Data on fertilizer purchases are used as a proxy for fertilizer use; other data are source-specific estimates.	0.63
Spatial Congruity	3	The emission factor is a global value. Because the variance of emissions across regions and across states is expected to be high.	10	States use state-level activity data to estimate statewide emissions.	0.30
Temporal Congruity	5	The emission factor is based on measured emissions over a crop year or calendar year. The emission factor is expected to vary significantly over time.	10	States use annual activity data to estimate annual emissions.	0.50
				Composite Score	0.40

Table 9.6-2
DARS Scores: Direct N_2O Emissions from Animal Production

DARS Attribute Category	Emission Factor Attribute	Explanation	Activity Data Attribute	Explanation	Emission Score
Measurement	5	IPCC (1997) did not document the source of the factor; it stated only that the factor was "derived on the basis of a very limited amount of information."	7	The value of 7 is a composite value, based on animal populations, default values for nitrogen excretion, and estimates of amount managed using daily spread or equivalent, based on sampling.	0.35
Source Specificity	10	The emission factor was developed specifically for N_2O emissions from animal production.	10	Data on animal populations are used to estimate nitrogen excretion.	1.00
Spatial Congruity	3	The emission factor is a global value. The variance of emissions across regions is expected to be high.	9	State values for animal populations are used; values for nitrogen excretion are global average values, but spatial variability is expected to be low.	0.27
Temporal Congruity	5	It is unknown whether the emission factor is based on measured emissions over a particular time frame. However, emissions are expected to vary significantly over the course of a year.	10	States use annual activity data to estimate annual emissions.	0.50
				Composite Score	0.53

Table 9.6-3
DARS Scores: Indirect N_2O Emissions from Manure and Fertilizer

DARS Attribute Category	Emission Factor Attribute	Explanation	Activity Data Attribute	Explanation	Emission Score
Measurement	3	The emission factor is based on reported N_2O emissions from nitrogen deposited on soil (i.e., it is based on direct emissions, not indirect emissions).	7	The value of 7 is a composite value, based on use of top-down statistics for fertilizer purchases; estimates of manure use based on sample data; and default values for (1) NOx and NH_3 volatilization, and (2) fraction of nitrogen that leaches.	0.21
Source Specificity	6	The emission factor is based on reported N_2O emissions from nitrogen deposited on soil (i.e., it is based on direct emissions, not indirect emissions). Variability is expected to be moderate to high.	9	Data on fertilizer purchases are used as a proxy for fertilizer use; other data are source-specific estimates.	0.54
Spatial Congruity	3	The emission factors are global values. The variance of emissions across regions is expected to be high.	5	State values for fertilizer use are used; values for (1) NOx and NH_3 volatilization and (2) fraction of nitrogen that leaches are global, and spatial variability is expected to be moderate to high.	0.15
Temporal Congruity	3	It is unknown whether the emission factor is based on measured emissions over a particular time frame. However, emissions are expected to be highly varied over the course of a year.	7	States use annual activity data to estimate annual emissions. However, there is a lag time between application of nitrogen and indirect emissions due to leaching; temporal variability is expected to be low to moderate.	0.21
				Composite Score	0.28

Table 9.6-4
DARS Scores: CO_2 Emissions from Agricultural Use of Limestone

DARS Attribute Category	Emission Factor Attribute	Explanation	Activity Data Attribute	Explanation	Emission Score
Measurement	5	Because the emission factors for each type of limestone are not based on measurement, the highest possible score is 5. The emission factors are based on mass balance.	8	Data on limestone purchases are used. Assuming use of top-down statistics on limestone sales is assumed; the breakdown between limestone and dolomite sales must be estimated.	0.40
Source Specificity	10	The emission factor was developed specifically for CO_2 from agricultural use of limestone.	9	The activity measured (limestone purchases) is very closely correlated with the emissions process.	0.90
Spatial Congruity	9	The emission factor is a global value. The variance of emissions across regions is expected to be low.	10	States use state-level activity data to estimate statewide emissions.	0.90
Temporal Congruity	9	The emission factor is not based on measured emissions over a particular time frame. However, the emission factor should not vary significantly over the course of a year.	7	States use annual activity data to estimate annual emissions. However, there is a lag time between application of lime and CO_2 emissions; temporal variability is expected to be low to moderate.	0.63
				Composite Score	0.71

7

REFERENCES

AAPFCO (American Association of Plant Food Control Officials) 1995. *Commercial Fertilizers 1996*. University of Kentucky, Lexington, KY.

Barnard, G., and Kristoferson, L. 1985. *Agricultural Residues as Fuel in the Third World*. Earthscan Energy Information Programme and the Beijer Institute of the Royal Swedish Academy of Sciences. London, England.

Bouwman, A.F. 1990. "Exchange of Greenhouse Gases between Terrestrial Ecosystems and the Atmosphere." In: Bouwman, A.F., ed. *Soils and the Greenhouse Effect*. John Wiley & Sons, Chichester. pp.61-127.

Byrnes, B.H., C.B. Christianson, L.S. Holt, and E.R. Austin. 1990. "Nitrous Oxide Emissions from the Nitrification of Nitrogen Fertilizers." In: Bouwman, A.F., ed. *Soils and the Greenhouse Effect*. John Wiley & Sons, Chichester. pp.489-495.

CAST (Council for Agricultural Science and Technology). 1992. *Preparing U.S. Agriculture for Global Climate Change*. Task Force Report No. 119. Waggoner, P.E., Chair. CAST, Ames, Iowa. June, 1992.

Eichner, M.J. 1990. "Nitrous Oxide Emissions from Fertilized Soils: Summary of Available Data." *Journal of Environmental Quality* 19:272-280.

IPCC (Intergovernmental Panel on Climate Change). 1999. 1. Estimation of Direct N_2O Emissions From Agricultural Soils. In: *Good Practice in Inventory Preparation. Agricultural Sources of Methane and Nitrous Oxide.* Draft Version.

IPCC (Intergovernmental Panel on Climate Change). 1997. *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Workbook.* IPCC. Bracknell, United Kingdom.

Mausbach, M.J. and Spivey, L.D. 1993. *Significance of Two Soil Components of the Pedosphere as Carbon Sinks*. Paper presented at the NATO Advanced Research Workshop on Soil Responses to Climate Change, Silsoe, Bedforshire, UK, 20-24 September.

Mosier, A. 1997. Telephone communication between Barbara Braatz of ICF Incorporated and Arvin Mosier of the Agricultural Research Service, U.S. Department of Agriculture, Fort Collins, CO. tel: 970-490-8250.

Strehler, A. and Stüzle, W. 1987. “Biomass Residues.” In: Hall, D.O. and Overend, R.P. (eds.) *Biomass*. John Wily and Sons, Ltd. Chichester, UK.

Tepordei, Valentin V. 1997. *Crushed Stone 1996* (U.S. Geological Survey Publication, 1997). Internet Address: http://minerals.er.usgs.gov/minerals/pubs/commodity/stone-crushed/.

Terry, D.L. 1997. Telephone communication between Beverly Grossman of ICF Incorporated and David Terry of the American Association of Plant Food Control Officials, University of Kentucky, Lexington, KY. tel: 606-257-2668.

Terry, D. L., and Paul Z. Yu. 1997. *Commercial Fertilizers 1996* (Washington, DC: The Fertilizer Institute) 1997.

TVA (Tennessee Valley Authority). 1993a. *Commercial Fertilizers*, *1993*. National Fertilizer and Environmental Research Center, Tennessee Valley Authority, TN. December 1993.

TVA. 1993b. *Fertilizer Summary Data*. National Fertilizer and Environmental Research Center, Tennessee Valley Authority, TN. December 1993.

USDA (1994) *Field Crops: Final Estimates, 1987-1992*: Statistical Bulletin Number 896. U.S. Department of Agriculture, National Agricultural Statistics Services, GPO, Washington, D.C.

U.S. EPA (U.S. Environmental Protection Agency). 1999. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 - 1997*. EPA 236-R-99-003. Internet address: http://www.epa.gov/globalwarming/inventory/1999-inv.html.

U.S. EPA (U.S. Environmental Protection Agency). 1998. *Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks (1990-1996)*. EPA-236-R-99-006. Internet address: http://www.epa.gov/globalwarming/inventory/1998-inv.html.